Coordination Challenges for Autonomous Spacecraft

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Abstract

While past flight projects involved a single spacecraft in isolation, over forty proposed future missions involve multiple coordinated spacecraft. This paper presents characteristics of such missions in terms of properties of the phenomena being measured as well as the rationale for using multiple spacecraft. We describe the coordination problems associated with operating these missions and identify needed technologies.

1. Introduction

The past few years have seen missions with growing numbers of probes. Pathfinder has a lander and rover (Sojourner), Cassini includes an orbiter and the Huygens lander, and Cluster II has 4 spacecraft for multi-point magnetosphere plasma measurements. This trend is expected to continue to progressively larger fleets. For example, one proposed interferometer mission [1] would have 18 spacecraft flying in formation in order to detect earth-sized planets orbiting other stars. Another proposed mission involves 44 to 104 spacecraft in Earth orbit to measure global phenomena within the magnetosphere.

To date over 40 multiple platform (multi-spacecraft) missions have been proposed, and they can be grouped into 3 families depending on why multiple platforms were proposed:

- multi-point sensing for improved coverage when observing/exploring large areas (like the satellites with passive microwave radiometers for the Global Precipitation Mission and similar sensors on the Global Electrodynamics Mission, Leonardo-BRDF, and the Magnetospheric Constellation);
- building large synthetic aperture sensors with many small spatially separated sensors for imaging very remote targets (like Constellation-X, Terrestrial Planet Finder, and TechSat-21); and
- specialized probes with explicitly separate science objectives (like coincident Mars Program missions or the PM train within the Earth Observing System).

While these reasons for having multiple platforms in a mission are not exclusive, they do have a major impact on how the resulting missions are formulated and managed. For instance, the Air Force's TechSat-21 mission concept [2] involves a distribution of clusters of platforms. Each cluster forms a synthetic aperture for radar sensing, and the number of clusters depends on the desired global coverage. While the operations of spacecraft in a cluster must be closely choreographed to make each joint observation, the operations between clusters are only loosely coordinated to determine how to allocate observations to clusters.

There are currently large efforts focused on formation flying and communications between spacecraft. This paper focuses on operations issues related to managing future multiple platform missions. While automating operations for a distributed constellation of orbiters has been addressed for communications satellites, these results do not apply directly to science missions due to cost reasons. Communications satellites are designed with cost in mind, but they also need large resource margins in order to handle growing markets. Science missions are designed with tight resource margins to minimize cost while flying spacecraft that are just capable enough to answer the motivating scientific questions.

In the next section, we describe the rationale for multiple platform missions in terms of the phenomena being measured. We then characterize open issues in managing different families of multiple platform missions and then describe similar issues for autonomy technologies currently in development. We then characterize the coordination problems that must be addressed by these technologies. This paper aims to analyze coordination problems for a class of domains and does not give a survey of coordination techniques that address them.

2. Multiple Platform Rationale

Science missions measure phenomena in various locations by making remote/local observations with active/passive sensors in one of five classes of planet centric orbits shown in Figure 1. Taking a more formal view, we can characterize phenomena in terms of a spatially and temporally grouped set of signals and a mission in terms of an information transfer system [3] to get the information from signals into the scientists' hands in order to facilitate answering questions. For instance, the constellation-X telescopes measure x-ray spectra of points

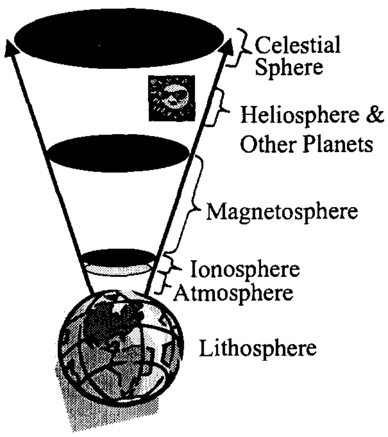

Figure 1: The locations of relevant phenomena

on the celestial sphere. Here each signal is a time varying x-ray spectrum.

Following this information transfer approach to characterize a mission, we can formally characterize phenomena along five metrics with respect to answering the motivating questions:

- *Signal location* involves which sphere contains the phenomena's signals (affecting orbit selection);
- *Signal isolation* involves separating spatially distinct signals within a target phenomenon;
- *Information integrity* involves the noise inherent to signals related to the phenomenon;
- *Information rate* involves how fast the signals change and have to be sampled; and
- *Information predictability* involves the probability of catching signals pertaining to a phenomenon during an observation.

We identify three rationales behind multi-platform missions: signal separation, signal space coverage, and signal combination. The following subsections describe these.

Signal Separation

This rationale arises from a desire to separate signals related to the target phenomena both from each other and from extraneous signals to account for signal isolation and information integrity issues respectively. For instance, the proposed Terrestrial Planet Finder (TPF) [4] will search for earth sized planets orbiting other stars and detect key spectral signatures to find signs of life. To do this the mission needs a 0.75 milli-arcsec angular resolution. Thus the instrument needs to isolate signals that are 0.75 milli-arcsec apart on the celestial sphere. This isolation requirement motivates a tightly controlled formation of five spacecraft that simulates a spacecraft with a kilometer wide telescope (see Figure 2), which orbits either around the L2 Lagrange point or trails behind the earth.

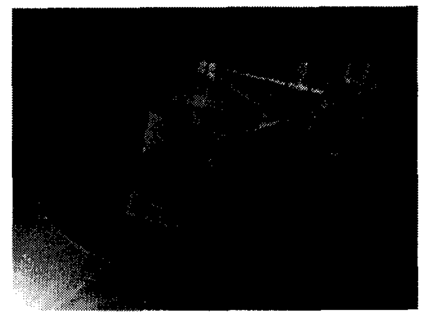

Figure 2: Five spacecraft TPF interferometer (picture from NASA TPF Website)

On the information integrity side, faint sources on the celestial sphere motivate either large detectors or long measurement integration times to capture enough of the signal to separate it from background noise. In the case of faint high-information-rate sources, the only solution is multiple spacecraft to implement a large enough detector. For instance, four satellites are proposed for Constellation-X to take simultaneous observations of X-ray sources on the celestial sphere while orbiting the L2 point. By providing a large enough detector, this mission will be able to measure short-lived X-ray phenomena like flares around other stars and events around black holes.

In terms of mission design, signal separation issues motivate actively flying spacecraft in formations around a reference orbit. This facilitates implementing both kilometer sized interferometers for signal isolation and multiple simultaneous remote sensors for improving information integrity. In both cases, the phenomena are remote respect to the collection of spacecraft.

Signal Space Coverage

This rationale arises from a desire to use a sensor web that measures whole regions of the signal space related to a phenomenon often enough to account for high information rates or low information availabilities. For instance, the proposed Magnetospheric Constellation mission (MC) [5] will study how the magnetotail stores, transports, and releases matter and energy. Here information availability is fairly low because the magnetotail is unstable and prone to catastrophic phenomena like magnetospheric substorms, which are not precisely predictable. The only way to measure particle and field signals within such a phenomenon involves having probes on site when the substorm occurs, which motivates multiple probes spread over multiple orbits to maximize the probability of observing the phenomenon (see Figure 3).

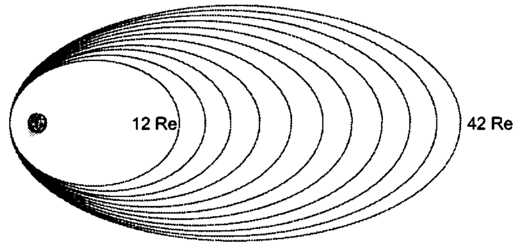

Figure 3: The orbits for the 50 to 100 nano-satellite Magnetospheric Constellation

On the high information rate side, the global precipitation mission (GPM) [6] objective is to measure the time varying global rainfall. The main reason for an evenly distributed constellation of orbiters looking at the atmosphere involves a need to sample every point on the globe every 3 hours. This information rate is driven by the speed in which thunderstorms can form and dissipate.

In terms of mission design, signal space coverage motivates distributing spacecraft evenly over a region either along the mission's orbits or about a reference orbit. The distribution facilitates implementing a sensor web to measure phenomena that are in-situ with respect to the population of spacecraft. For GPM and MC "in-situ" means continuous observation of the entire atmosphere and large regions of the magnetotail respectively. For other missions with spacecraft clustered around a reference orbit "in-situ" means intermittent observation of a select region about the reference orbit (e.g. global electrodynamics and magnetospheric multi-scale missions).

In either case, the spacecraft in the sensor web require formation knowledge for combining measurements to observe the underlying phenomenon, but precise formation control is not necessary. While some formation geometries are preferable to others, each formation has a high spacecraft positioning tolerance.

Signal Combination

While the previous rationales focused on single missions with multiple coordinated platforms, this rationale derives from attempts to get multiple missions with separate platforms to coordinate. One example involves getting five separate missions within the Earth Observing System to coordinate their observations (see Figure 4). For instance, CloudSat has a millimeter-wave radar to observe clouds and precipitation, and Calipso has a polarization-sensitive lidar for observing vertical profiles of aerosols and clouds. Each mission was designed around separate questions, but combining signals enables answering questions about relationships between aerosols and precipitation.

Figure 4: Combining signals in the EOS (picture from CloudSat Website)

As this example implies, this rationale motivates missions flying in a close string-of-pearls formation, where there is a strict ordering of the spacecraft. The first spacecraft ignores all the rest, and each other spacecraft ignores its successors while flying in formation with its immediate predecessor. For instance, CloudSat flies in formation with Callipso, which flies with Aqua.

The international science community is planning sixteen missions to Mars over the next ten years, and these missions will cooperate in multiple ways. Earlier missions will provide precision approach navigation for later missions, and real-time tracking for critical events like descent and landing or orbit insertion. Orbiters will provide relay services to landed assets and positioning services to rovers and other mobile "scout" missions. All missions will cooperate on radiometric experiments and maintain a common time reference for relating data between missions. These features have been conceptualized as a "Mars Network" of orbiting satellites [9]. While all missions will improve the potential for collecting data on Mars by placing multiple sensors, actually realizing this potential requires treating the multiple missions as a single meta-mission with signal combination from platforms distribute about Mars. Given that the landers and rovers use positioning information from orbiters, these missions can be characterized as a "string of pearls" where rovers follow positioning information from orbiters.

In general, there is a tremendous similarity between signal combination and signal separation rationales. Signals are combined to separate out the different phenomena components of each signal. The only real difference between these two rationales derives from the underlying evolution of a program's mission set. Signal separation issues motivate multiple platforms for a single mission, and signal combination opportunities motivate launching new spacecraft that take advantage of the observations made by older spacecraft. Thus signal combination leads to a string of pearls with a predecessor relationship between the spacecraft instead of clusters where each spacecraft is cognizant of all its neighbors.

Multiple Rationales

Often a mission has more than one motivating question, and each question can involve a different class of phenomena raising a different rationale for multiple platforms. For instance, the mission concept motivating TechSat-21, a US Air Force mission [2], involves a set of clusters of spacecraft evenly distributed on a circular orbit (see Figure 5). Multiple spacecraft cluster together to improve signal separation for radar imaging and clusters break up to improve signal space coverage for enabling point-to-point communications.

Leonardo-BRDF, a proposed NASA mission [7], extends on this by having all three rationales for multiple platforms. This mission involves a number of spacecraft observing the Earth with various optical sensors from a number of angles to determine how light reflected from the earth varies with the angle – the "Bidirectional Reflectance Distribution Function" (BRDF). To improve signal isolation, a larger spacecraft cluster improves the measurement of a location's BRDF by increasing number of angles sampled over a short interval. On the other hand, a larger number of smaller spacecraft clusters improves signal space coverage, and letting investigators insert spacecraft with different sensors results in enabling signal combination for an evolving mission.

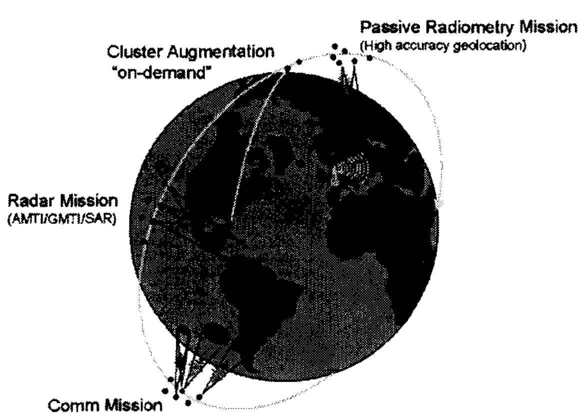

Figure 5: Mission concept motivating TechSat-21 (picture from TechSat-21 Website)

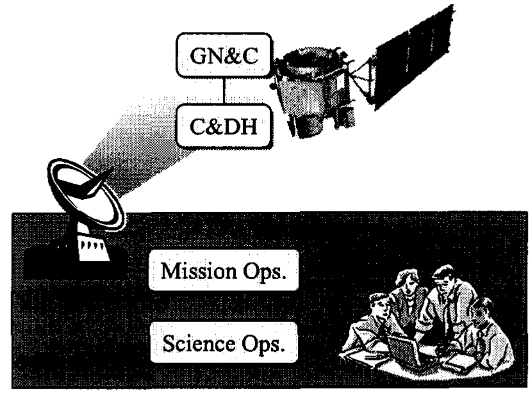

Figure 6: Typical model of spacecraft operations

3. Ground Operations Issues

At its most abstract level, operating a spacecraft involves five feedback loops (see Figure 6). The tightest loop involves the guidance, navigation, and control (GN&C) system, which articulates the spacecraft hardware to satisfy commands like measuring a phenomenon or despinning a reaction wheel. This system is subsequently controlled by the command and data-handling (C&DH) system, which passes commands to the GN&C to collect data and transmit it to ground. The mission operations center takes this data and controls the C&DH by analyzing telemetry in the data to determine spacecraft health and sending up the next batch of commands to execute. The desired measurements that motivate these commands are specified by the science operations center, which takes the science component of past-transmitted data and poses new measurement requests. Finally the scientific community controls science operations by taking science data products produced by the science operations center and posing questions that motivate generating new science products.

Current practices that place multiple instruments on a spacecraft complicate this process by breaking science operations into multiple instrument-operations teams to service different scientific communities. These teams compete for spacecraft resources and submit a prioritized list of measurement requests to mission operations, which tries to satisfy as many requests as possible. Another added complication comes from multiple missions having to negotiate over access to deep space antennas. Here multiple mission operations teams schedule time on antennas weeks to months in advance to communicate with the C&DH system of their respective spacecraft.

The movement to multiple platform missions further complicates this process by increasing the number of GN&C and C&DH systems that the mission operations center has to manage. The main issues here involve reducing the rate at which the required mission operations staff grows with the number of spacecraft and overcoming cross-platform instrument-calibration and data-validation complexities within science operations.

Missions typically have to face a cost-risk tradeoff when focusing on operations. One way to keep this tradeoff under control involves using spacecraft that are made robust by an expensive over abundance of onboard resources, and another involves underutilizing cheaper spacecraft by enforcing very conservative resource margins. Both keep risk constant while reducing operations cost by simplifying operations complexity. Unfortunately neither performs well over the ultimate cost per bit of scientific information metric. The first dramatically increases the spacecrafts' costs while the second decreases the amount of science data collected. The approach focused on here involves using automation.

Signal Space Coverage

Current work on multiple platform control automation has been spearheaded by companies like ORBCOMM [8], which operate constellations of 37 communications satellites (see Figure 7). This work focuses on a signal-space coverage mission, and treats each spacecraft as an isolated entity to automate as much of its mission operations as possible. While the result was impressive in that ORBCOMM was able to automate all but investigating anomalies and developing operational workarounds, the underlying problem was easier than that of a science mission. A communications satellite is simpler than a probe with a sensor suite to answer a number of scientific questions. Also, a communication's constellation only has one goal to transfer data from one location to another, it lacks a science operations team to manage/calibrate instruments and to change the daily measurement regime for a scientific community.

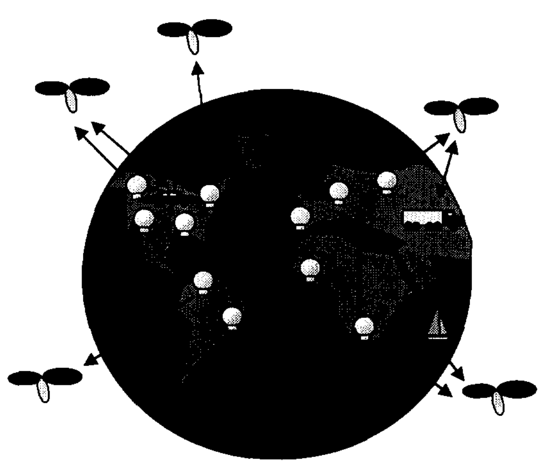

Figure 7: The ORBCOMM communications structure

Thus ORBCOMM provides a point solution for a signal space coverage mission that has a large number of ground stations distributed around the planet. This distribution further simplifies the satellites by turning them into simple repeaters between a local ground station and a mobile terminal. This simplification with the single objective facilitates automating most ground operations activities. Extending this solution to science missions involves improving anomaly detection and diagnosis techniques to handle more complex spacecraft, and adding planning and scheduling automation to manage these spacecraft as well as respond to new science requests.

Signal Separation

While the ORBCOMM approach might be extendable to missions with spacecraft distributed for signal space coverage, it does not extend well to missions with cluster or string-of-pearl formations – for signal separation. Formation flying spacecraft require GN&C systems that communicate in order to determine and control relative spacecraft positions and orientations. For instance, StarLight [10] will involve two formation flying spacecraft in an earth-trailing orbit to implement a large interferometer (see Figure 8). Each spacecraft has a large disk-shaped sunshade to keep the optics dark, and a collector spacecraft reflects light from a star to a combiner spacecraft. The combiner then uses this light with light directly from the star to measure an interference pattern to downlink. Combining multiple interference patterns results in generating a single image with enough resolution to see a star's planetary system.

From the perspective of the GN&C and C&DH, the main issue revolves around precision and robustness. The spacecraft have to attain and maintain a formation that is a kilometer across with centimeter positioning precision and even greater positioning knowledge. Also, there is no such thing as a truly safe operating mode for a formation flyer.

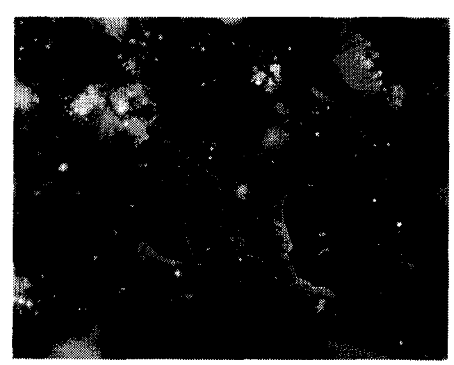

Figure 8: The StarLight Mission with its two spacecraft interferometer (from StarLight Website)

The standard technique of just pointing solar panels sunward and listening for commands is problematic if it results in formation flyers drifting apart. For instance, StarLight is only required to have the spacecraft fly at most 2-Km apart, but the spacecraft cross-link is designed to support communications up to a 200-Km distance just in case of drift during an anomaly. For the same reason, both spacecraft will be able to communicate directly to Earth

The mission operations center for a signal separation mission has its own issues to surmount. These involve optimizing observation ordering, minimizing anomaly response time, and maintaining coordination across multiple spacecraft. Since each observation requires time and propellant to reconfigure a formation, optimally ordering observations results in being able to gather more data. This need to minimize time and propellant usage also motivates a rapid response to anomalies. The farther the spacecraft drift apart during an anomaly, the more time or propellant it will take to get them back together. Both lost time and lost propellant result in lost observations. Finally mission operations has to craft coordinated sequences for multiple C&DH systems, and these sequences must respond appropriately to anomalies both within and between spacecraft. While sequence coordination is not much of a problem for the two-spacecraft StarLight mission, the five-spacecraft TPF (see Figure 2) will have coordination issues.

Finally, the science operations center will have to validate measurements collectively taken by multiple spacecraft. This validation will involve more than just determining the health and calibration of a single instrument. Since instruments will be distributed across the cluster, cross-calibration is needed between spacecraft in combination with calibrated cluster position, orientation, and configuration measurements.

Signal Combination

Signal combination missions have easier formation requirements, but the complexity moves into coordinating multiple science and mission operations centers for the collaborating missions. Here each spacecraft can fly in isolation, but the operations centers have to coordinate their command generation processes in order to maximize science collection not only within each mission, but also across all collaborating missions. For instance consider EO-1 following less than a minute behind Landsat-7, as depicted in Figure 9. Here EO-1 flies relative to Landsat-7, but Landsat-7 is oblivious to EO-1.

In the case of EO-1, the coordination was fairly painless. All the Landsat-7 operations staff had to do was determine Landsat-7 targets in isolation and then pass them to the EO-1 operations crew. Since EO-1's goal was to test its instrument technologies, there was no need for

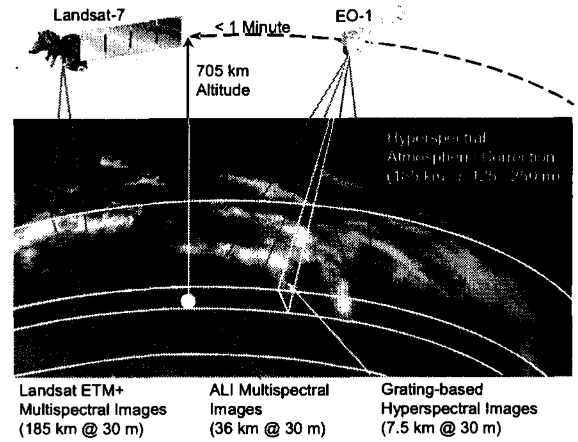

Figure 9: Earth Observer-1 following Landsat 7

EO-1 to affect Landsat-7's operation. In general this will not be the case and operations centers will have to coordinate their command generation in order to facilitate answering questions that motivate coincident observations from multiple sensors on different spacecraft.

4. Autonomous Operations Issues

The previous section pointed out where segments in the spacecraft control structure are made more complex when adapted to a multiple platform mission. While communications companies have automated much of a constellation's operations, their results do not directly apply to the more complicated evolving demands of science missions. Fortunately research within the space autonomy community has been focusing on automating the operations of complex missions. The question is, "How well will this technology generalize to complex multiple platform missions?"

The main thrusts of autonomy research involve reducing costs and enabling missions that focus on phenomena with high information rates and low information predictabilities. This research can be grouped in terms of three technologies:

- *Robust execution* includes performing activities with automatic mode estimation & recovery using models of how spacecraft subsystems behave, to broadly cover anomalies within the modeled subsystems;
- *Planning and scheduling* involves determining when to perform which activities as a spacecraft's capabilities and science collection goals evolve; and
- *Science analysis* involves processing observation data onboard a spacecraft to determine both the value of observations as well as new science collection goals.

While the first two technologies focus on raising the level where mission operations commands a spacecraft, the

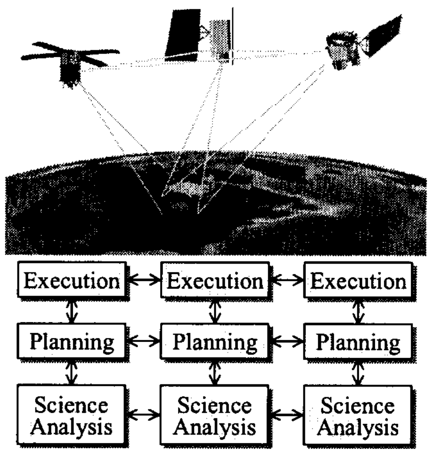

Figure 10: Autonomy technology interactions

third raises the level of science operations' interaction. Instead of prioritized observation lists and timed command sequences, mission and science operations respectively produce situation dependent activity determination strategies and data dependent observation strategies. The goal of raising the spacecraft commanding level is to reduce latency in responding to anomalies as well as the detection of observation opportunities by closing as many control loops as possible onboard the spacecraft. The Techsat-21 mission (Figure 5) will demonstrate onboard science analysis, replanning, robust execution, and model-based estimation and control [11].

Multiple platform issues arise upon considering how the three systems motivated by these technologies distribute across the collection of spacecraft. There are multiple ways varying from putting all three systems on a single spacecraft that treats the others as slaves to putting all three systems on each spacecraft and having them collaborate as peers. Assuming a peer-to-peer approach, the multiple platform issues can be characterized in terms of implementing the horizontal interactions between systems in Figure 10. Among these interactions, those between execution systems are used to facilitate executing coordinated activities like formation flying and multiple platform observations. Those between planning systems similarly facilitate determining when to perform which coordinated activities, and those between science analysis modules facilitate both cross-platform data fusion and letting one platform send new science goals to another.

While signal space coverage missions will have little need for the horizontal interactions, the other two rationales will motivate cross-links. The earlier operations issues mentioned for signal combination missions map onto a need to provide horizontal interactions between planning and science analysis systems, and those for signal separation missions at least motivate execution systems on each spacecraft with cross-links. In the case of those signal separation missions where cross-links periodically break and reestablish, like those to measure the magnetosphere, this intermittent communications loss also motivates distributing onboard planning/scheduling and science analysis systems that interact.

5. Coordination Challenges

Now we describe the coordination challenges for each of the three autonomy thrusts. As mentioned previously, depending on the rationale behind the mission, coordination may not be needed among components at all levels.

<u>Execution</u>

- Coordinated measurement
  Spacecraft that perform coordinated measurements often require constant communication and processing for cross-calibration and fault diagnosis and correction in both measurement and motion control.
- Local and shared resources
  The execution system must ensure that the spacecraft does not oversubscribe local and shared resources. In the case of orbiters, shared resources could be communication bandwidth to downlink data, memory to store data, or the spacecraft themselves for investigating a shared target. Surface explorers may additionally share physical space.
- Uncertainty, failure, and recovery
  The timing of events and consumption of resources can only be estimated. Activities can fail, subcomponents can malfunction, and the state of the spacecraft may need to be estimated, diagnosed, and corrected. During coordinated measurements, the spacecraft must also monitor and perform mode estimation and diagnosis on each other. If one spacecraft is failing to operate sufficiently, the execution systems may decide to restart a measurement, fail the coordinated activity, or continue with sacrificed accuracy or precision.

<u>Planning and scheduling</u>

- Local and shared activities
  Over a fixed or varying duration, an activity for a spacecraft can consume depletable metric resources (such as fuel or energy), use non-depletable metric resources (such as power), replenish resources (solar power) or change states (position, operating modes). The start time, duration, and state and resource changes of an activity may be functions of other variables (e.g. energy = power · duration). The environment may also change states and resource levels (e.g. day/night). The planner/scheduler is responsible for ensuring safe resource levels and states by adding, deleting, or

rescheduling activities as motivated by science goals dictated by the science analysis module. Coordinating the planners in this respect requires that they resolve conflicts over shared states and resources as well as those involving joint activities that can violate local constraints. The planners must reach consensus in when and how they perform these joint activities.

- Communication constraints
Inter-spacecraft communication and communication with ground is limited in bandwidth and latency. Spacecraft can only communicate in windows determined by orbits and ground antenna availability. The planner must model these constraints and track local power and memory resources that communication affects. Coordinated planning strategies that ignore these communication constraints may fail to establish consensus among the joint activities of the spacecraft.
- Computation constraints
Different spacecraft have different processors and storage devices that are shared by different components. The performance of the flight computer is usually limited because it is designed for harsh environments. This heterogeneity will affect the usefulness of different coordination strategies. For example, a centralized approach may perform better than a peer-to-peer approach for spacecraft with widely varying computational resources.
- Uncertainty, failure, and recovery
A planner can estimate timing and resource consumption, but in order to forecast the effects of future events, it needs feedback from the execution system about the state and the success of activities. This feedback can result in broken commitments to other spacecraft, requiring re-coordination at the planning level.
- Metrics
Spacecraft performance is evaluated according to scientific gain. This corresponds to the amount of data transmitted and the value of that data. The planner/scheduler is responsible for coordinating its activities with others to maximize the summed value of the downlinked data.
- Cooperation / negotiation
The multiple spacecraft participating in a single mission may cooperate to answer the same scientific questions. (In many cases, however, different scientists manage different instruments on a single platform and negotiate over local resources on the spacecraft.) For multiple missions, planners may negotiate over shared resources, such as bandwidth to transmit data to ground.

<u>Science analysis</u>

- Communication constraints
Distributed science analysis can involve the transfer of large images and must be designed around communication constraints described earlier.
- Computation constraints
Onboard science analysis can potentially be expensive if processing large images. A coordination strategy must adapt to the different computational capabilities of the spacecraft.
- Uncertainty, failure, and recovery
An autonomous science analysis module may predict the value of science targets for closer investigation and/or decide whether to retry a failed investigation. It may also detect new, unexpected opportunities and decide how to distribute them to the spacecraft planners.
- Metrics
Mission performance is measured in terms of both scientific gain and cost. A good strategy must address the previous coordination issues to handle science goals and analysis in a way that increases scientific value while reducing operations costs. The distributed analysis modules may increase science throughput by only reporting data that they judge to be interesting and downlinking only the interesting part of the data (e.g. by cropping images). This also reduces the costs associated with manually processing large datasets and images on the ground.
- Cooperation / negotiation
Spacecraft may cooperate/negotiate to perform measurements for each other to increase the scientific value of their data.

6. Conclusions

This paper described multiple platform space missions in terms of properties of a mission's scientific objectives. Despite the observation location, the rationale determines how the spacecraft populate the orbit. There are three rationales: signal separation, signal combination, and signal space coverage. These rationales respectively motivate a single cluster of spacecraft flying in formation around the orbit, a string of spacecraft flying close together on the orbit, and a distribution of spacecraft evenly spread along the orbit.

Regardless of whether a standard or autonomous approach to mission management is adopted, several issues need to be addressed before flying a multiple platform mission. For a signal space coverage mission, the main issue is to automate as much of operations as possible to minimize the people-per-spacecraft ratio. However, this requires no special coordination technology. The main issues include needs for

- anomaly detection and response automation to reduce effort in fixing intermittent anomalies and

- planning and scheduling automation to reduce daily effort in handling new science requests.

To this pair of issues, signal combination between missions raises extra issues to facilitate collaboration either between operations staffs or autonomous spacecraft. These issues include needs for

- collaboration techniques to merge observation priorities both within and between missions and
- coordination techniques to optimize the planned data gathering activities of multiple spacecraft satisfying these merged priorities.

Finally signal separation missions raise their own unique issues that derive from formation flying and instruments distributed across multiple spacecraft in order to make a single measurement. The main issues include the added difficulties of

- anomaly detection and response both within and between formation fliers,
- planning and scheduling to minimize fuel used to reconfigure a formation between observations and during anomaly response, and
- validating data collected by multiple spacecraft.

We then characterized the coordination problems autonomous multi-platform missions face at the execution, planning, and science analysis levels. In addition to the challenges listed, different missions may warrant different levels of autonomy, and coordination strategies must address how the human operator is involved.

This paper's rationale-based approach to analyzing multiagent domains may help characterize the coordination needs of some other domains. Although many domains, such as robotic soccer, are not clearly related to multi-spacecraft missions, autonomous unmanned vehicles serve similar roles to spacecraft. They are typically used to identify targets and neutralize them (by taking measurements or attacking).

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